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(12) UK Patent Application (19) GB (11) 2 372 578 (13) A

(43) Date of A Publication 28.08.2002

(21) Application No 0123245.3

(22) Date of Filing 27.09.2001

(30) Priority Data
(31) 0104384 (32) 22.02.2001 (33) GB
(31) 0106092 (32) 13.03.2001
(31) 0106338 (32) 14.03.2001

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(51) INT CL^7
G02B 6/12

(52) UK CL (Edition T)
G2J JGDA

(56) Documents Cited
WO 2000/010039 A1

(58) Field of Search
UK CL (Edition T) G2J JGDA JGDBX
INT CL^7 G02B
ONLINE: WPI, EPODOC, JAPIO

(54) Abstract Title
Optical waveguide device with recessed slab region

(57) A semiconductor optical waveguide device comprises a semiconductor rib waveguide having an elongate rib portion 10 and slab regions 13 on immediately adjacent opposite lateral sides of the rib portion 10. The rib portion 10 extends above the slab regions 13 where, at least one of the slab regions 13 including a recess 36 spaced apart from the rib portion 10. An un-doped lateral wall 39 of the recess 36 provides a lateral boundary (referred to herein as "the recess lateral wall boundary") of the rib waveguide such that in use it laterally confines an optical wave propagated by the waveguide. One or more doped regions 18, 20 may be situated adjacent to the waveguide. The horizontal electrically insulating layer 14 may be made from silica and the substrate 16 may be made from silicon. Electrically conductive contacts 22, 24 made from metal can also be included, and are arranged in electrical contact with the doped regions 18, 20.

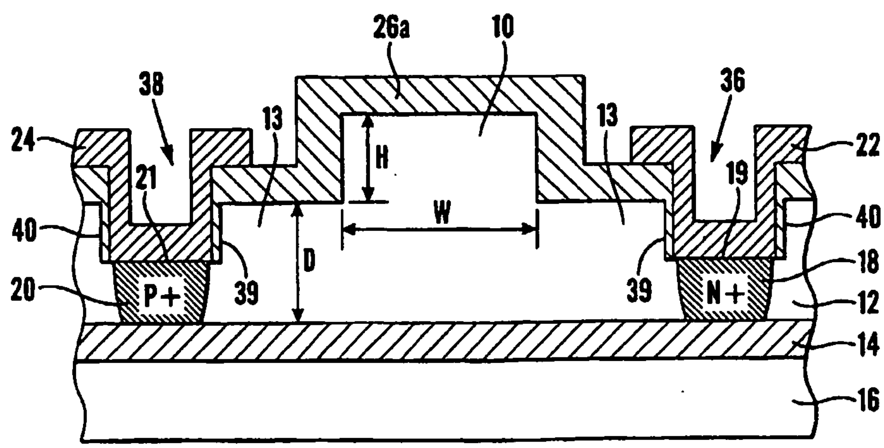
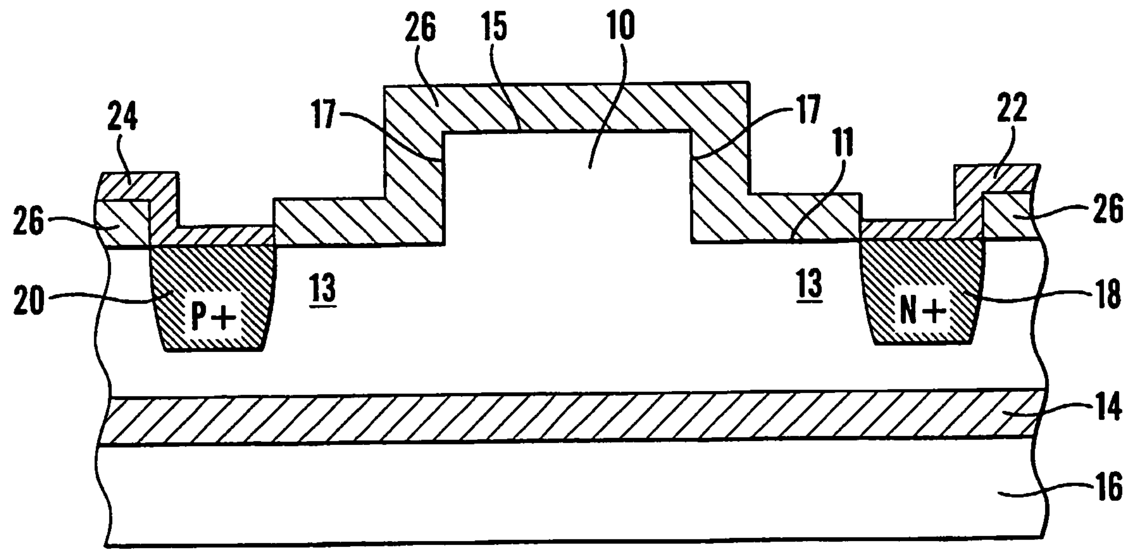


Fig.2

GB 2 372 578 A

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.



26
15
10
24
17
17
22
11
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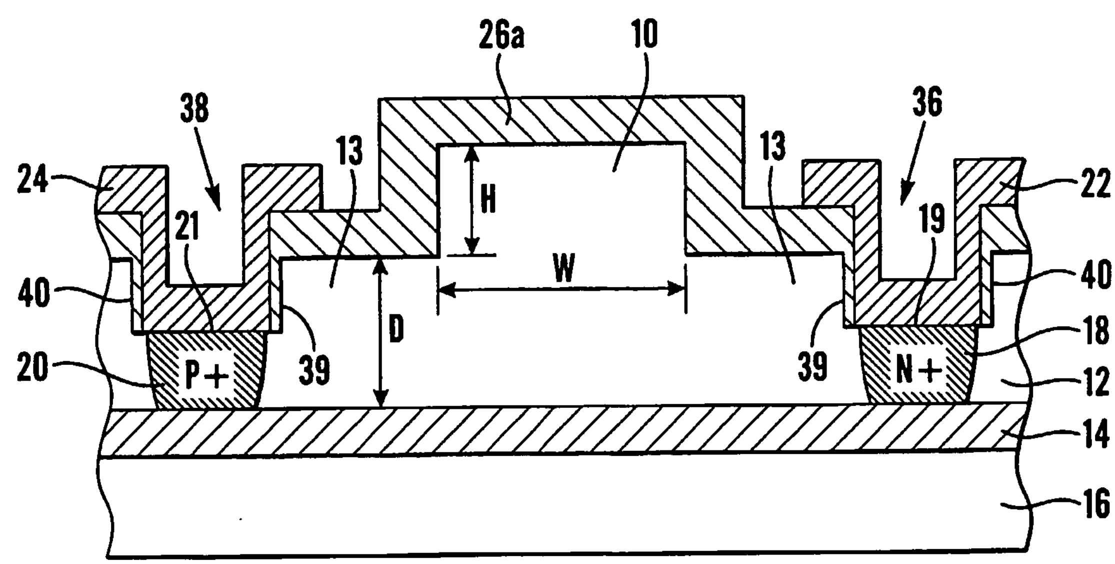
26
20
P+
13
13
N+
18
14
16

Fig.1



26a
10
38
36
13
13
24
22
H
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19
W
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40
18
39
D
39
20
P+
N+
12
14
16

Fig.2

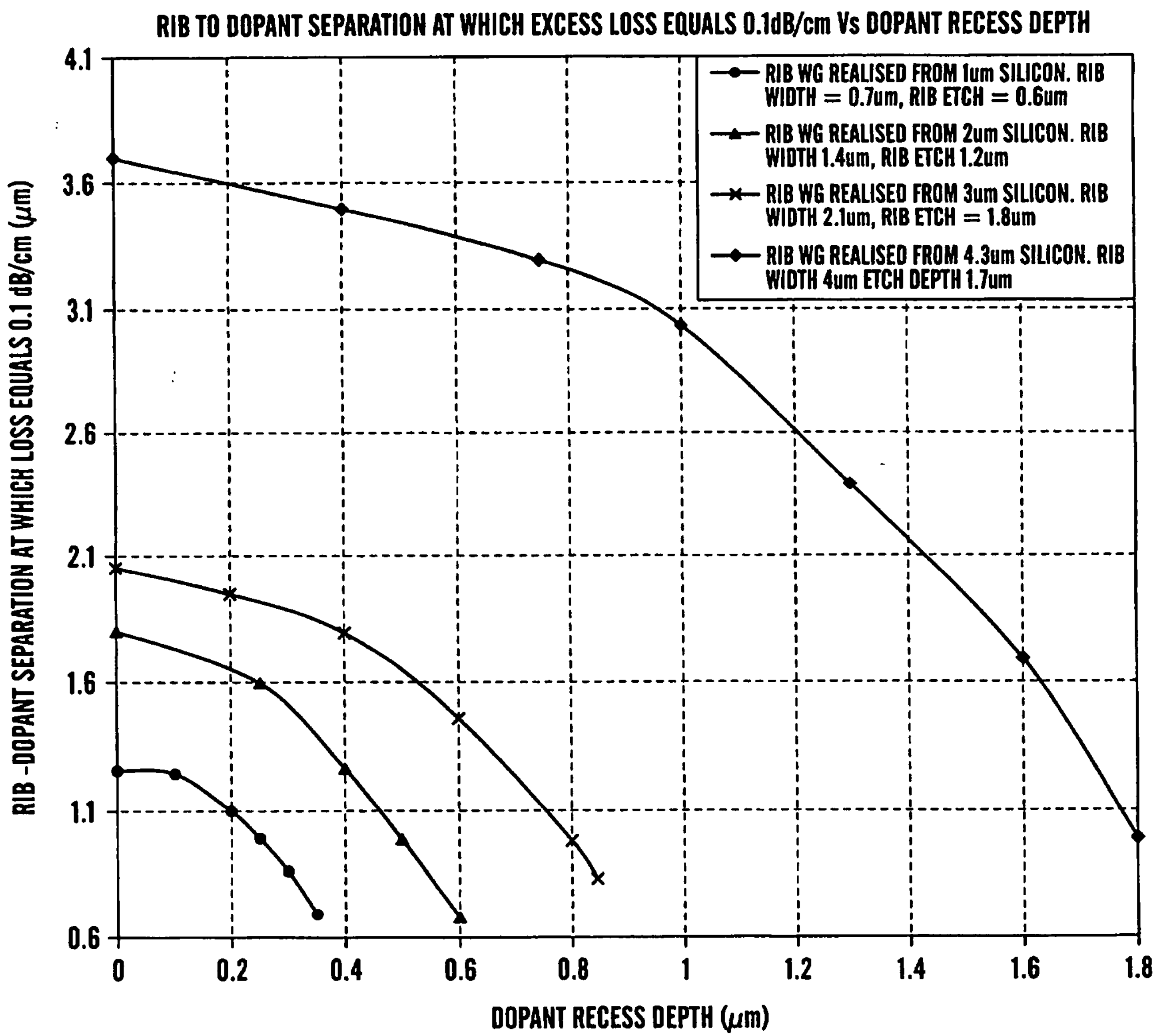
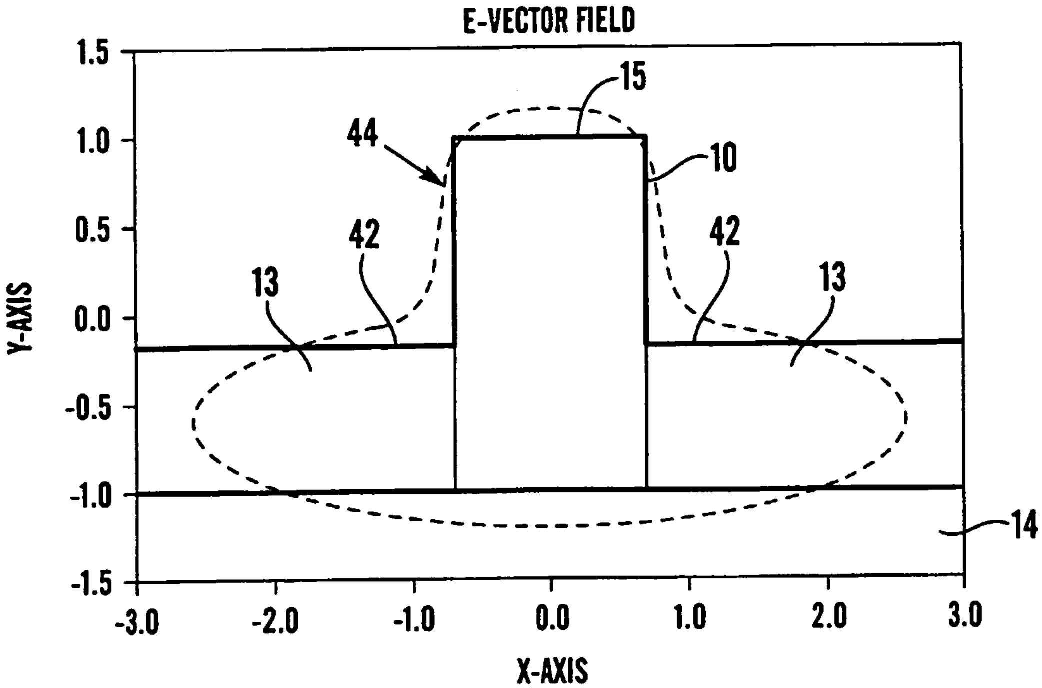

RIB TO DOPANT SEPARATION AT WHICH EXCESS LOSS EQUALS 0.1dB/cm Vs DOPANT RECESS DEPTH
RIB WG REALISED FROM 1um SILICON. RIB WIDTH = 0.7um, RIB ETCH = 0.6um
RIB WG REALISED FROM 2um SILICON. RIB WIDTH 1.4um, RIB ETCH 1.2um
RIB WG REALISED FROM 3um SILICON. RIB WIDTH 2.1um, RIB ETCH = 1.8um
RIB WG REALISED FROM 4.3um SILICON. RIB WIDTH 4um ETCH DEPTH 1.7um
RIB -DOPANT SEPARATION AT WHICH LOSS EQUALS 0.1 dB/cm (μm)
4.1
3.6
3.1
2.6
2.1
1.6
1.1
0.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
DOPANT RECESS DEPTH (μm)

Fig.3


E-VECTOR FIELD
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Y-AXIS
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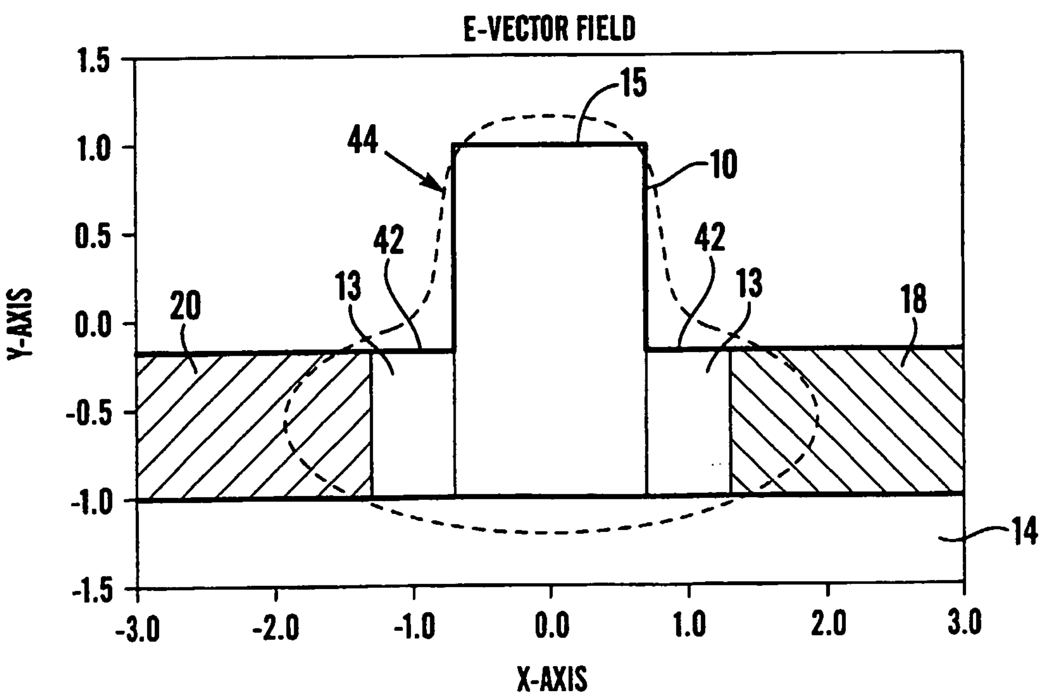
-2.0
-1.0
0.0
1.0
2.0
3.0
X-AXIS
15
44
10
42
42
13
13
14

Fig.4(a)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X-AXIS
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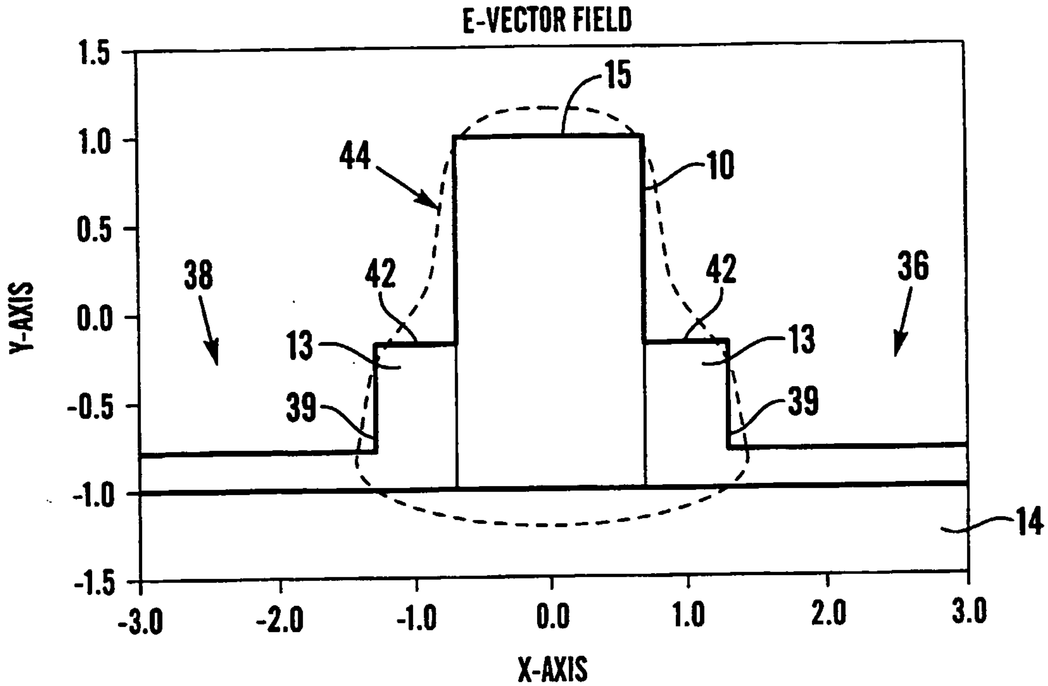
42
20
13
13
18
14

Fig.4(b)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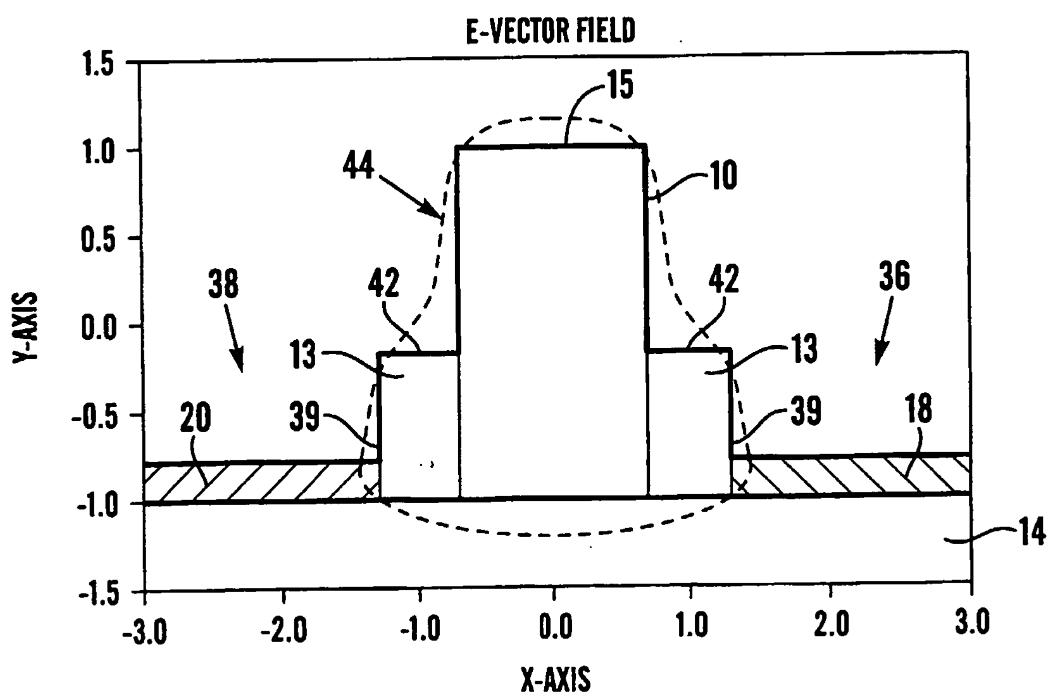
0.0
1.0
2.0
3.0
X-AXIS

Fig.4(c)


E-VECTOR FIELD
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1.0
0.5
0.0
-0.5
-1.0
-1.5
Y-AXIS
15
44
10
38
42
42
36
13
13
20
39
39
18
14
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
X-AXIS

Fig.4(d)

Semiconductor Optical Waveguide Device

The present invention relates to semiconductor optical waveguide devices, and particularly to their use in electro-optic modulators.

Semiconductor optical waveguide devices in which the semiconductor material is doped to produce p and/or n doped regions are very well known. For example, semiconductor rib waveguide devices are known in which a p-i-n diode is formed across the waveguide such that charge carriers are injected into the region of the waveguide in which an optical wave propagates (during use). The p-i-n diode therefore acts as an electro-optic modulator since the injection of charge carriers into the semiconductor waveguide affects the complex effective refractive index of the waveguide, and thereby affects the phase and amplitude of the optical wave propagating therein.

There is a continual need to produce ever faster and more efficient electro-optic modulators. Examples of where such modulators are needed include optical computers (e.g. next generation supercomputers), optical switches for optical spectrum analysing (e.g. in multiplexers / demultiplexers), and low cost external modulators (e.g. for optical fibre local loop telecommunications applications).

A problem associated with such known devices is that there is a conflict between, on the one hand, the speed and efficiency of the p-i-n diode, and on the other hand the efficiency of the waveguide itself. This is because, in order to induce fast, substantial, changes in the effective refractive index of the waveguide (so that fast and effective changes to the phase and/or amplitude of the optical wave may be produced), the doped regions must be located as close as possible to the optical wave; however, any overlap between the optical wave and the doped regions causes optical losses in the waveguide. There is therefore a need to produce a fast and efficient electro-optic modulator which does not suffer from high unintended optical losses.

It is also known to provide a doped region adjacent to a semiconductor waveguide in order to absorb stray light which is not guided by the waveguide, for example as disclosed in PCT Patent Application No. PCT/GB98/01145 published as WO 99/28772 (Bookham Technology) and/or as disclosed in UK Patent Application No. GB 0023133.2 (Bookham Technology); the entire disclosures of both of these specifications are incorporated herein by reference. One use of such arrangements is optically to isolate adjacent waveguides, for example so that a plurality of adjacent waveguides may be positioned closer to each other to increase the compactness of an optical device. It would therefore be advantageous to be able to reduce the separation between such a doped region and a waveguide without inducing extra optical losses in the waveguide.

Silicon rib optical waveguides having p-i-n diodes formed across them are disclosed in, for example, US Patent No. 5,757,986 and PCT Patent Application No. PCT/GB99/02537 published as WO 00/10039 (both from Bookham Technology), and European Patent No. EP 0 524 213 B1 (Siemens).

It would also be desirable generally to be able to reduce the size, in particular the width, of semiconductor optical waveguides such that the optical wave propagated by the waveguide is more confined than in presently known devices. This would have the advantage of enabling waveguides to be positioned closer together, this being particularly advantageous for waveguide arrays, for example, in which a plurality of waveguides are arranged next to each other in a well defined configuration.

According to a first aspect, the present invention provides a semiconductor optical waveguide device, which comprises a semiconductor rib waveguide comprising an elongate rib portion and slab regions on immediately adjacent opposite lateral sides of the rib portion, the rib portion extending above the slab regions, at least one of the slab regions including a recess spaced apart from the rib portion, an un-doped lateral wall of the recess providing a

lateral boundary (referred to herein as "the recess lateral wall boundary") of the rib waveguide such that in use it laterally confines an optical wave propagated by the waveguide.

According to a second aspect, the invention provides a semiconductor optical waveguide device, which comprises a semiconductor rib waveguide and one or more doped regions situated adjacent to the waveguide, the waveguide comprising an elongate rib portion and slab regions on immediately adjacent opposite lateral sides of the rib portion, the rib portion extending above the slab regions, at least one of the slab regions including a recess spaced apart from the rib portion, an un-doped lateral wall of the recess providing a lateral boundary (referred to herein as "the recess lateral wall boundary") of the rib waveguide such that in use it laterally confines an optical wave propagated by the waveguide.

By "lateral" is meant lateral with respect to the direction of propagation of an optical wave along the waveguide, i.e. lateral with respect to the direction of elongation of the rib portion of the waveguide.

The first aspect of the invention has the advantage that because the un-doped lateral wall of the recess laterally confines the optical wave propagated by the waveguide, the waveguide may be smaller in width than known semiconductor waveguides, without inducing significant optical losses. The second aspect of the invention has the additional advantage that because the un-doped lateral wall of the recess laterally confines the optical wave propagated by the waveguide, the (or each) doped region may be positioned closer to the optical wave than in known devices, without inducing significant optical losses. For embodiments of the invention in which the (or each) doped region is used to isolate adjacent waveguides, this has the advantage of enabling adjacent waveguides to be positioned closer together. For embodiments of the invention which comprise a modulator, it has the advantage of increasing the efficiency of the device. Additionally, the invention provides

the possibility of reducing the lateral dimensions (e.g. the diameter) of the optical wave (i.e. "squashing" the optical wave), thereby (as already mentioned) enabling adjacent waveguides to be positioned closer together and/or enabling two or more doped regions on opposite sides of the optical wave to be positioned closer together. This latter advantage has the further advantage of enabling the switching speed of a modulator to be increased, for example.

The rib portion preferably comprises an upper surface and two lateral surfaces. By "upper" is meant upper with respect to the slab regions of the waveguide "above" which the rib portion extends; it is not meant to denote any particular orientation of the waveguide with respect to gravity.

In preferred embodiments of the invention, each of the slab regions on opposite lateral sides of the rib portion includes a recess, an un-doped lateral wall of which provides a lateral boundary of the rib waveguide ("a recess lateral wall boundary of the waveguide") such that in use it laterally confines an optical wave propagated by the waveguide. Preferably the, or each, recess lateral wall boundary of the waveguide is the closer, to the rib portion, of two lateral walls of the recess. The, or each, recess preferably comprises two lateral walls and a base. Each lateral wall of a said recess may be substantially perpendicular to an upper surface of the slab region in which it is formed. Alternatively, at least part of one or each lateral wall of a said recess may be inclined with respect to a plane perpendicular to the upper surface of the slab region.

Each recess lateral wall boundary of the waveguide is spaced apart from the rib portion of the waveguide. Preferably, the distance by which each recess lateral wall boundary of the waveguide is spaced apart from the rib portion of the waveguide is less than the lateral width of the rib portion.

Where present, the, or each, doped region preferably is situated no closer to the rib portion than the, or each, recess lateral wall boundary of the waveguide. More preferably the, or each, doped region extends from the base

of a said recess. Most preferably, the, or each, doped region extends from the base only of a said recess.

In preferred embodiments, the device further comprises a lower optical confinement layer spaced apart from the rib portion and the, or each, recess.

It is preferred for the semiconductor to be silicon. It is especially preferred for the device to comprise a so-called "silicon-on-insulator" device, in which a horizontal electrically insulating layer, normally formed from silica, forms the lower optical confinement layer. Below the optical confinement layer there is preferably a substrate, preferably also formed from silicon.

Particularly preferred dimensions of one embodiment of a device according to the invention are as follows. Preferably the rib portion has a lateral width of 3 μm or less, more preferably 2 μm or less. The distance by which each recess lateral wall boundary of the waveguide is spaced apart from the rib portion of the waveguide is preferably 2 μm or less, more preferably 1 μm or less. Preferably the, or each, recess has a depth of at least 0.2 μm.

More generally, however, the inventors of the present invention have found that the depth of the, or each, recess as a proportion of the depth of the slab region in which the recess is located (e.g. from the upper surface of the slab to a lower optical confinement layer) is normally a critical factor in determining how closely the doped region may be spaced from the rib portion for a given maximum acceptable optical loss. In particular, the inventors have found that if the depth of the, or each, recess is at least 25% of the depth of the slab region in which the recess is located, then the lateral dimensions of the optical wave may be reduced (i.e. the optical wave may be "squashed" laterally) without inducing unacceptable optical losses. That is to say, a recess depth of 25% of the depth of the slab region in which the recess is located has been found to be the depth at which the optical wave may be begun to be squashed while maintaining the optical loss induced by the close proximity of the doped

region(s) at an acceptable level. Recess depths of greater than 25% of the depth of the slab region, for example at least 30%, preferably at least 35%, more preferably at least 40%, especially at least 50%, of the depth of the slab region, generally enable greater squashing of the optical wave, and hence smaller separations between the doped region(s) and the rib portion, for a given maximum acceptable optical loss. The given maximum acceptable optical loss is preferably 0.1 dB/cm.

The device preferably comprises a p-doped region (more preferably a p^+-doped region) situated on one lateral side of the waveguide and an n-doped region (more preferably an n^+-doped region) situated on the opposite lateral side of the waveguide. More preferably, the device comprises a p-i-n diode. Most preferably, the device comprises an optical modulator.

The invention will now be described, by way of example, with reference to the accompanying drawings, of which:

Figure 1 is a cross-sectional view of a known lateral p-i-n diode device;

Figure 2 is a cross-sectional view of an embodiment of a device according to the invention;

Figure 3 is a graphical representation showing the effect of recess depth upon the minimum separation between the doped regions and the rib portion for a given constant acceptable optical loss, for a range of sizes of device according to the invention; and

Figure 4 (views (a) to (d)) are schematic cross-sectional diagrams illustrating the laterally confining effect of the recesses of embodiments of devices according to the invention, in comparison with known devices.

Figure 1 shows a standard SOI (silicon-on-insulator) rib waveguide with a lateral injection p-i-n diode made by diffusion into a layer of silicon. In this arrangement, the waveguide comprises a rib portion 10 extending above upper surfaces 11 of slab regions 13 on opposite lateral sides of the rib portion, the slab regions also forming part of the waveguide. The rib portion 10 comprises an upper surface 15 and lateral surfaces 17. Above the rib portion 10 is a layer of silica 26. Extending from the upper surfaces 11 of the slab regions on each lateral side of the rib portion are doped regions 18 and 20. Region 18 is a p^+-doped region and region 20 is an n^+-doped region. Electrically conductive contacts 22 and 24 (formed from metal) are arranged in electrical contact with the p^+-doped and n^+-doped regions, respectively, and these enable the p-i-n diode to be electrically biased. The silica layer 26 extends above the slab regions and away from the diode adjacent to the doped regions, with the contacts 22 and 24 extending above it. Below the rib portion 10, the doped regions 18 and 20, and the slab regions 13 is a silica layer 14 which functions as a lower optical confinement layer. Below the silica layer 14 is a substrate layer of silicon 16.

Figure 2 shows a waveguide device according to the invention. The device is identical to that shown in Figure 1 except that each slab region 13 includes a recess. On one lateral side of the rib portion 10 is recess 36, and on the opposite lateral side of the rib portion is recess 38. An n^+-doped region 18 extends from the base 19 (only) of recess 36, and a p^+-doped region 20 extends from the base 21 (only) of recess 38. Each recess 36, 38, comprises a pair of lateral walls 39 and 40. Lateral wall 39 of each recess, namely the lateral wall closer to the rib portion 10, provides a lateral boundary ("the recess lateral wall boundary") of the rib waveguide such that in use it laterally confines an optical wave propagated by the waveguide. The silica layer 26a situated above the slab regions 13 and the rib portion 10, extends into each recess 36 and 38 and covers each lateral wall 39, 40 of each recess. This prevents the lateral walls of the recesses being doped when the base of the recesses is doped, for example by ion implantation. This is particularly important for lateral walls 39 which

provides a lateral boundary ("the recess lateral wall boundary") of the rib waveguide, so that there is substantially no overlap between an optical wave propagated through the waveguide, and the doped regions 18 and 20, which would tend to cause unwanted optical losses.

Figure 3 is a graphical representation showing the effect of recess depth upon the minimum horizontal separation between the doped regions and the rib portion at which the optical loss is a given acceptable value (namely 0.1 dB/cm), for a range of sizes of device according to the invention. This separation is termed the "minimum acceptable separation" herein. The data shown in Figure 3 were produced by means of computer modelling calculations. Each of the devices modelled had the general form of the device shown in Figure 2, and the relevant dimensions, namely rib height (H), rib width (W) and slab depth (D) are indicated in Figure 2.

In Figure 3, the data indicated, respectively, by the circles, the triangles, the crosses and the diamonds is for devices having the following dimensions:

	Rib Height H (μm)	Rib Width W (μm)	Slab Depth D (μm)
●	0.6	0.7	0.4
▲	1.2	1.4	0.8
×	1.8	2.1	1.2
◆	1.7	4.0	2.6

It can clearly be seen for each of the devices modelled that the minimum acceptable horizontal separation between the rib portion and each doped region decreases as the recess depth increases. More particularly, it can be seen that at shallower recess depths, increasing the depth of the recesses has little affect upon the minimum acceptable separation, whereas at deeper recess depths, increasing the depth of the recess has a larger affect upon the minimum acceptable separation. In fact, it can be seen that, for each of the devices modelled, once the depth of the recesses has reached approximately 25% of the depth of the slab region, increasing the depth of the recess has a larger affect upon the minimum acceptable separation than it does for recess depths of less than approximately 25% of the slab depth.

Views (a) to (d) of Figure 4 show cross-sections through semiconductor rib waveguide devices with superimposed computer-modelled optical wave profiles illustrating the cross-sectional (lateral) extent of optical waves propagated by the waveguides – indicated by the grey shaded regions outlined by the dashed lines 44. In each of the views, the X-axis and the Y-axis are scaled in μm. Each of the waveguide devices has a rib portion 10 having a width W of 1.4 μm, a height H (between the upper surface 15 of the rib portion and the upper surfaces 42 of the immediately adjacent slab regions 13) of 1.17 μm, and a depth D of the slab regions 13 (between the upper surfaces 42 of the slab regions and the upper extent of the optical confinement layer 14) of 0.83 μm.

Views (a) and (b) of Figure 4 show conventional semiconductor rib waveguide devices, without recesses provided in their slab regions 13. Figure 4(a) shows a device without doped regions, and Figure 4 (b) shows a device with doped regions 18 and 20 on each side of the rib portion. As already mentioned, the extent of the optical wave propagated along the waveguides (as modelled by computer) is illustrated by the grey shaded regions and outlined by the dashed lines indicated 44. In Figure 4(a) the optical wave has a very wide lateral extent, of approximately 5 μm at its maximum width in the slab regions 13 of the waveguide. In Figure 4(b), the doped regions 18 and 20 laterally confine the optical wave somewhat, so that its maximum width is approximately 3.8 μm in the slab regions of the waveguide. However, it is clearly shown in Figure 4(b) that the optical wave overlaps to a large extent with each of the doped regions. The maximum lateral distance by which the optical wave encroaches into each doped region is approximately 0.6 μm in the device shown in Figure 4(b). This high degree of overlap with the doped regions results in optical losses in the propagation of the optical wave of approximately 8 dB/cm or higher, which renders the device impracticable.

Figures 4(c) and 4(d) show optical wave profiles for semiconductor waveguide devices according to the invention. In each case, the difference between the devices of the invention and those shown in views (a) and (b) is that the devices of views (c) and (d) each have recesses 36 and 38 in the slab regions 13, the recesses being spaced apart laterally from the rib portion by approximately 0.6 μm. Each recess 36 and 38 has a wall 39 which provides a lateral boundary ("a recess lateral wall boundary") of the rib waveguide which laterally confines the optical wave, as indicated by the much narrower profile 44 shown in views (c) and (d) compared to views (a) and (b). The maximum width of the optical wave in the slab region 13 in both views (c) and (d) is approximately 2.8 μm (compared to 5 μm for view (a) and 3.8 μm for view (b)). Additionally, there is minimal overlap (of approximately 0.1 μm) between the optical wave and the doped regions in the device shown in view (d) resulting in

an acceptable optical loss of approximately 0.1 dB/cm (compared to 8 dB/cm or higher for the device of view (b)).

Claims

1. A semiconductor optical waveguide device, which comprises a semiconductor rib waveguide comprising an elongate rib portion and slab regions on immediately adjacent opposite lateral sides of the rib portion, the rib portion extending above the slab regions, at least one of the slab regions including a recess spaced apart from the rib portion, an un-doped lateral wall of the recess providing a lateral boundary (referred to herein as "the recess lateral wall boundary") of the rib waveguide such that in use it laterally confines an optical wave propagated by the waveguide.

2. A device according to Claim 1, further comprising one or more doped regions situated adjacent to the waveguide.

3. A device according to Claim 1 or Claim 2, in which each of the slab regions on opposite lateral sides of the rib portion includes a recess, an un-doped lateral wall of which provides a lateral boundary ("a recess lateral wall boundary") of the rib waveguide such that in use it laterally confines an optical wave propagated by the waveguide.

4. A device according to any preceding claim, in which the, or each, recess lateral wall boundary of the waveguide is the closer, to the rib portion, of two lateral walls of the recess.

5. A device according to any preceding claim, in which the distance by which each recess lateral wall boundary of the waveguide is spaced apart from the rib portion of the waveguide is less than the lateral width of the rib portion.

6. A device according to Claim 2 or any claim dependent thereon, in which the, or each, doped region is situated no closer to the rib portion than the, or each, recess lateral wall boundary of the waveguide.

7. A device according to Claim 2 or any claim dependent thereon, in which the, or each, doped region extends from the base of a said recess.

8. A device according to Claim 7, in which the, or each, doped region extends from the base only of a said recess.

9. A device according to any preceding claim, further comprising a lower optical confinement layer spaced apart from the rib portion and the or each recess.

10. A device according to any preceding claim, in which the rib portion has a lateral width of 3 μm or less.

11. A device according to Claim 10, in which the rib portion has a lateral width of 2 μm or less.

12. A device according to any preceding claim, in which the distance by which each recess lateral wall boundary of the waveguide is spaced apart from the rib portion of the waveguide is 2 μm or less.

13. A device according to Claim 12, in which the distance by which each recess lateral wall boundary of the waveguide is spaced apart from the rib portion of the waveguide is 1 μm or less.

14. A device according to any preceding claim, in which the, or each, recess has a depth of at least 0.2 μm.

15. A device according to any preceding claim, in which the depth of the, or each, recess is at least 25% of the depth of the slab region in which the recess is located.

16. A device according to any preceding claim, comprising a p-doped region situated on one lateral side of the waveguide and an n-doped region situated on the opposite lateral side of the waveguide.

17. A device according to Claim 16, comprising a p-i-n diode.

18. A device according to any preceding claim, comprising an optical modulator.

The Patent Office

INVESTOR IN PEOPLE

Application No: GB 0123245.3
Claims searched: 1 - 18

Examiner: Andrew P Jenner
Date of search: 16 January 2002

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): G2J: JGDA, JGDBX

Int Cl (Ed.7): G02B

Other: Online: WPI, EPODOC, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A, P	WO 00/10039 A1 BOOKHAM TECHNOLOGY PLC - see figure 1	

X Document indicating lack of novelty or inventive step	A Document indicating technological background and/or state of the art.
Y Document indicating lack of inventive step if combined with one or more other documents of same category.	P Document published on or after the declared priority date but before the filing date of this invention.
& Member of the same patent family	E Patent document published on or after, but with priority date earlier than, the filing date of this application.

Application No: GB 0216143.8
Claims searched: All

Examiner: Helen Edwards
Date of search: 20 December 2002

Patents Act 1977 : Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
Y	6-16, 18-24	Journal of Lightwave Technology, Volume 19, number 3 March 2001, Improved Modulation Performance of a Silicon p-i-n Device by Trench Isolation, P. D. Hewitt and G. T. Reed
Y	6-16, 18-24	GB 2340616 A (BOOKHAM TECHNOLOGY LIMITED) See figure 2 and pages 4, 5 and 6
E, A	-	GB 2372578 A (BOOKHAM TECHNOLOGY PLC)
E, A	-	GB 2372576 A (BOOKHAM TECHNOLOGY PLC)

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{T}:

G2F

Worldwide search of patent documents classified in the following areas of the IPC^{7}:

G02F

The following online and other databases have been used in the preparation of this search report:

EPODOC, JAPIO, WPI